A Search for companions to nearby brown dwarfs: the binary DENIS-P J1228.2-1547

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Hubble Space Telescope near infrared camera and multiobject spectrometer (NICMOS) imaging observations of two nearby young brown dwarfs, DENIS-P J1228.2-1547 and Kelu 1, show that the DENIS object is resolved into two components of nearly equal brightness with a projected separation of 0.275 arcsec (5 astronomical units for a distance of 18 parsecs). This binary system can provide the first dynamical measurement of the masses of two brown dwarfs in only a few years. Upper limits to the mass of any unseen companion in Kelu 1 yield a planet of 7 Jupiter masses and age 0.5×10^9years, that would have been detected at a separation larger than $\sim$4 astronomical units. This example demostrates that giant planets could be detected by direct imaging if they exist in Jupiter-like orbits around nearby young brown dwarfs.

Brown dwarfs (BDs) are "failed stars", that is they are not massive enough to sustain stable hydrogen burning, but are sufficiently massive to start deuterium burning *(1)*. Brown dwarfs are more like giant planets than stars in that their luminosity and temperature drop continuously with time, and ultimately they become extremely cool and faint. The borderline between stars and BDs is estimated to be at about 0.075 solar masses ($M_\odot$) for solar metallicity *(2)*. The deuterium burning limit is at a mass of about 13 M_J, where M_J denotes a Jupiter mass ($\sim$0.001 $M_\odot$)*(3)*. We adopt this mass to separate BDs from planets in order to avoid the problems of a definition based on poorly understood formation mechanisms *(4)*. For many years BDs have eluded firm detection, but since 1995 several objects have been shown to be unambiguously substellar *(5)*. The evidence for BDs is based on observations of lithium *(6)*, luminosity and/or surface temperatures *(7)*. However, no direct mass measurement of a brown dwarf has been obtained to date. We present in this paper the first object for which this can be done in the near future.

The first free-floating BD discovered in the solar neigborhood was Kelu 1. It was found in a proper motion survey*(8)*. The second nearby free-floating BD was discovered by the DEep Near-Infrared Survey (DENIS). The DENIS and 2MASS surveys are ongoing and have the aim of yielding a complete sky coverage in the near-infrared I, J and K' bands *(9)*. The analysis of only 220 square degrees (about 1% of the planned DENIS survey) provided three objects *(10)* with I-J colors redder than GD 165B, which was the coolest BD candidate known before the discovery of Gl 229B *(11)*. The surface temperatures of Kelu 1 and the DENIS objects are not obviously low enough to establish a substellar status because young BDs and very low-mass stars can have the same effective temperature. The necessary distinctive substellar signature came from the spectroscopic detection of lithium in the atmospheres of Kelu 1 and DENIS-P J1228.2-1547 (hereafter abbreviated to DENIS 1228-15). *(12)*. On the other hand, in very low-mass stars the temperature and pressure at the bottom of the convection zone are high enough so that lithium gets rapidly destroyed via proton capture. The combination of high lithium abundance with low surface temperature implies that Kelu 1 and DENIS 1228-15 must have masses lower than 0.065 $M_{\odot}$ and ages younger than 10^9years (1 Ga) *(12)*.

We observed DENIS 1228-15 and Kelu 1 with NICMOS camera 1 (NIC1) on the Hubble Space Telescope (HST). The NIC1 data of DENIS 1228-15 was obtained on 2 June 1998, in multiple-accumulate mode with filters F110M, F145M, and F165M *(13)*. This instrumental configuration provides an optimal combination of throughput and spatial resolution. Our observations of Kelu 1 were obtained using the same configuration on August 14, 1998. The NIC1 images of DENIS 1228-15 resolved two components of similar brightness. To estimate the parameters of this binary system, we used an iterative approach: the data were modelled assuming two point sources and using both model and observed point spread functions (PSFs). The positions and the brightness ratios of the two point sources were free parameters, and the iterations continued until the residuals were similar to the noise. We obtained a separation of 0.275 ± 0.002 arcsec and a position angle of 41.0 ± 0.2^o. The apparent F110M, F145M and F165M magnitudes (respectively) on the HST-Vega system *(14)* are: DENIS 1228-15 A (15.69, 14.96, 13.98); DENIS 1228-15 B (15.89, 15.12, 14.13); Kelu 1 (14.13, 13.23, 12.37). The standard deviation of these magnitudes are less than 0.01 mag., but the systematic errors can be up to 0.1 mag. Our F165M magnitude of 12.37 for Kelu 1 is in agreement with the published H-magnitude of 12.32 *(8)*. The B/A flux ratio of the DENIS 1228-15 system increases toward longer wavelength (0.83 for F110M, 0.86 for F145M and 0.87 for F165M), indicating that DENIS 1228-15 B is slightly cooler than DENIS 1228-15 A. An independent confirmation of the binary nature of DENIS 1228-15 comes from public HST/NIC3 observations with filter F187N obtained on 24 June 1998 for another program by Hugh Jones and Todd Henry. The scale of NIC3 of 0.2 arcsec/pixel undersamples the PSF (theoretical full width half maximum of 0.16 arcsec at 1.87μm). Within the uncertainties due to the undersampling, the fitted values for the NIC3 data are in agreement with the results derived from the NIC1 data.

The trigonometric parallaxes of DENIS 1228-15 and Kelu 1 are not known yet, although they can be obtained with ground-based telescopes *(15)*. The distance to Kelu 1 has been estimated from its proper motion to be in the range 10–12 pc *(8)*. The distance to DENIS 1228-15 was estimated using spectroscopic parallax for the unresolved binary *(10)*. The binarity implies that the object is more distant than previously thought. Using our NIC1 photometric magnitudes for the primary, we estimate a distance of 18±4 pc. For such distance, the observed angular separation corresponds to a projected binary separation of 4.95±1.10 astronomical units (A.U.).

Masses for DENIS 1228-15 A and B are unknown, but the presence of lithium implies a mass of less than 0.06 $M_\odot$ for the primary *(12)*. If, for example, both components have masses around 0.05 $M_\odot$, the orbital period would be $\sim$35 years for a semimajor axis of 5 A.U. In only one year HST will be able to detect the orbital motion. The two known BD companions to nearby stars have much larger separations and consequently much longer orbital periods *(16)*, yet orbital motion may already have been seen in Gl 229B*(17)*. By following up for several years the orbital motion of DENIS 1228-15, we can determine the orbital solution, and thus dynamical masses for the individual substellar components. An exact mass determination is necessary for testing and calibrating theoretical evolutionary models of substellar objects, and to investigate their initial mass function.

The presence of one binary among the two first discovered field free-floating BDs suggests that substellar multiple systems may be common, although we note that there is a strong selection effect in favor of BD binaries. In flux limited surveys like those that led to the discoveries of DENIS 1228-15 and Kelu 1, the volume sampled for binaries is up to $\sqrt{2}^3 = 2.8$ times larger than for single brown dwarfs. Despite of this selection effect, it appears to be easier to find substellar companions to BD primaries than around stellar primaries as indicated by the lack of BDs found in radial velocity surveys *(18)*. Substellar multiple systems may form in relatively isolated molecular clumps. Several free-floating BD candidates have been identified in star forming regions *(19)*. The existence of low-mass pre-stellar clumps has been revealed by millimeter observations of nearby star-forming regions *(20)*. The process of formation of a BD is probably similar to that of a star, the main difference being the initial mass of the collapsing rotating clump. Very young BDs (1–10 Myr) should have disks around them *(21)* where planets could form. Because BDs are intrinsically faint and do not settle on the main-sequence, the brightness contrast between a BD and a planet is more favorable than the contrast between a star and a planet *(22)*.

In Figure 2, we show the detection limit (3 σ) for faint companions to Kelu 1 in the F165M filter after subtraction of a PSF constructed from our library of NIC1 observations of BD candidates in the Pleiades *(23)*. For separations larger than 0.3 arcsec we would have detected a companion 6.7 magnitudes fainter in F165M than Kelu 1. The age of Kelu 1 has been constrained to the range 0.3–1.0 Ga on the basis of the presence of lithium and its temperature of about 1900 K *(24)*. The H-band magnitude of Kelu 1 at a distance of 12 pc would correspond to a mass of approximately of 0.065 $M_\odot$ for an age of 0.5 Ga (0.07 $M_\odot$ for an age of 1 Ga). In Figure 2, we have converted magnitude differences to masses, using current evolutionary models for brown dwarfs and giant planets *(25)*. A planet with a mass of about 7 Jupiter masses (M_J) orbiting Kelu 1 at a separation larger than 4 A.U. would have been detected. For an age of 1 Ga, the detection limit would rise to a companion with 20 M_J at 4 A.U. The age dependence of mass limits as a function of magnitude difference limits is illustrated by the comparison between the solid line (0.5 Ga) and the dashed line (1.0 Ga) in Figure 2. The example of Kelu 1 shows that it is feasible to detect superplanets with masses in the range 5–10 M_J with direct imaging in orbit around nearby young BD primaries if they have separations typical of the giant planets in the solar system (5–30 A.U.).

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26. Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract No. NAS5-26555. We thank the Director of the Space Telescope Institute for granting us HST Director Discretionary time. GB acknowledges the support of NSF through grant AST96-18439. E.L.M. was supported by a postdoctoral fellowship of the Spanish Ministerio de Educación y Cultura.

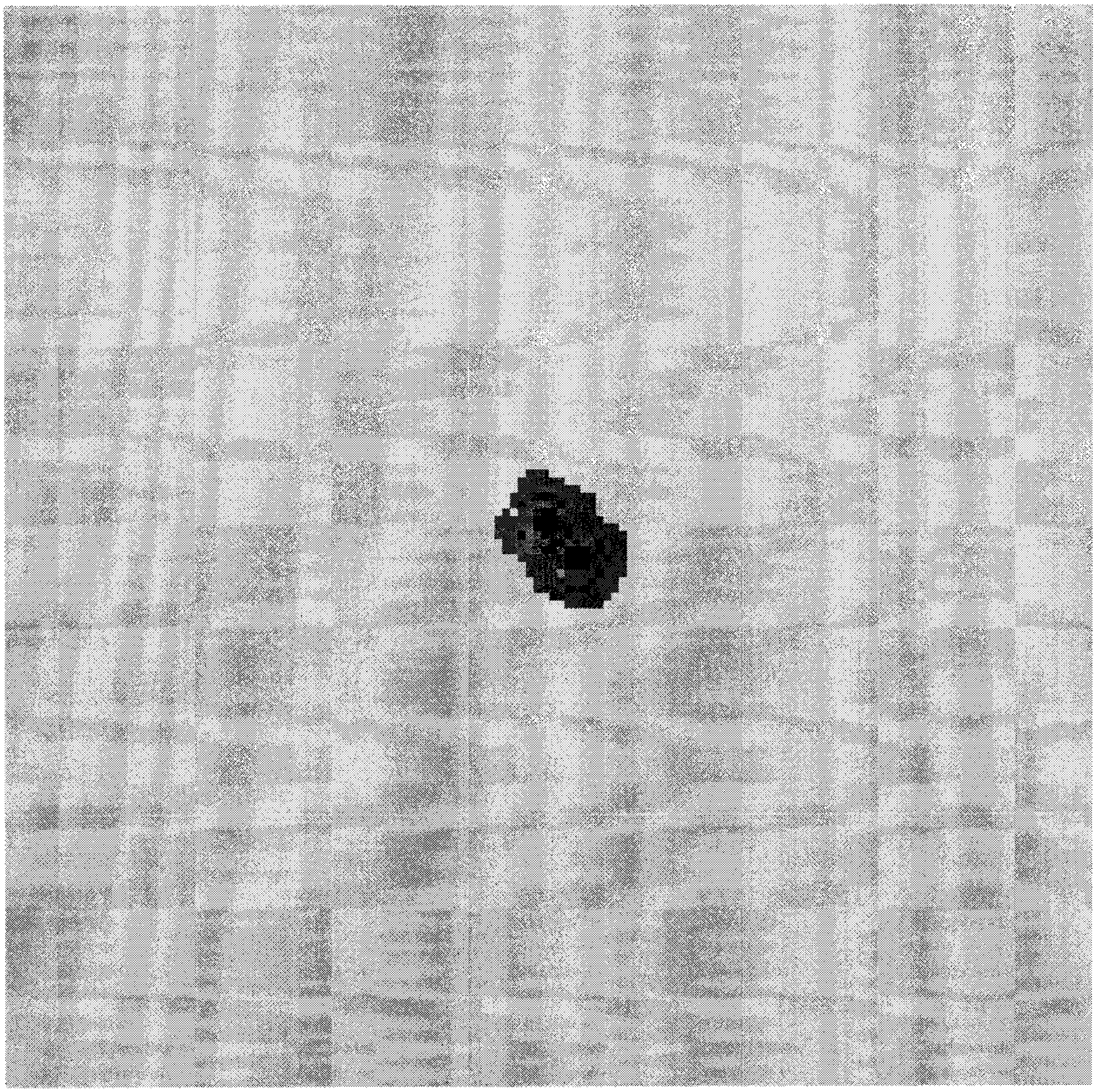

Fig. 1.— A section (6 arcsec x 6 arcsec) of the combined NIC1 F110M, F145M and F165M images of DENIS 1228-15. North is up and east left. There are no other sources brighter than m_{F165M} ~20 in the field of view of our NIC1 frame.

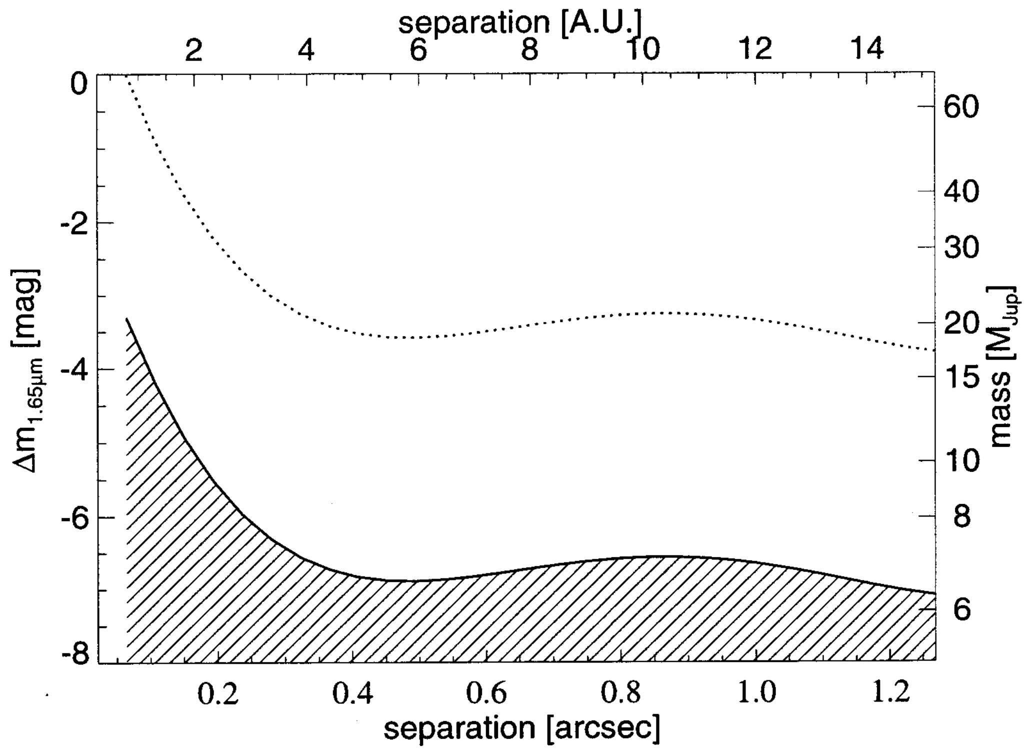

Fig. 2.— Detection limits for faint companions in the NIC1 F165M image of Kelu 1 after PSF subtraction. We used a primary age of 0.5 Ga and mass of 0.065 $M_{\odot}$ for calculating the mass limits corresponding to magnitude difference limits. The dotted line indicates the mass limits for an age of 1.0 Ga.